Deciphering spectral fingerprints of habitable exoplanets

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Deciphering Spectral Fingerprints of Habitable Exoplanets

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Abstract

We discuss how to read a planet's spectrum to assess its habitability and search for the signatures of a biosphere. After a decade rich in giant exoplanet detections, observation techniques have advanced to a level where we now have the capability to find planets of less than 10 Earth masses (M_{Earth}) (so-called "super Earths"), which may be habitable. How can we characterize those planets and assess whether they are habitable? This new field of exoplanet search has shown an extraordinary capacity to combine research in astrophysics, chemistry, biology, and geophysics into a new and exciting interdisciplinary approach to understanding our place in the Universe. The results of a first-generation mission will most likely generate an amazing scope of diverse planets that will set planet formation, evolution, and our planet into an overall context. Key Words: Habitable planets—Exoplanet search—Biomarkers—Planetary atmospheres. Astrobiology 10, 89–102.

1. Introduction

Sagan *et al.* (1993) analyzed a spectrum of Earth taken by the Galileo probe that searched for signatures of life and concluded that the large amount of O_2 and the simultaneous presence of CH_4 traces are strongly suggestive of biology. To characterize a planet's atmosphere and its potential habitability, we look for absorption features in the emergent and transmission spectrum of the planet (see Fig. 1). The spectrum of the planet can contain signatures of atmospheric species, that is, what creates its spectral fingerprint. On Earth, some atmospheric species that exhibit noticeable spectral features in the planet's spectrum result directly or indirectly from biological activity; the main atmospheric species are O_2, O_3, CH_4, and N_2O. CO_2 and H_2O are, in addition, important as greenhouse gases in a planet's atmosphere and as potential sources for high O_2 concentration from photosynthesis.

The detection of an Earth-like planet is approaching rapidly as a result of radial velocity surveys (HARPS), transit searches (CoRoT, Kepler), and space observatories dedicated to the characterization of such a discovery. These search techniques and strategies are already in development phase (James Webb Space Telescope), as are large ground-based telescopes (extremely large telescopes, the Thirty Meter Telescope, the Giant Magellan Telescope) and dedicated

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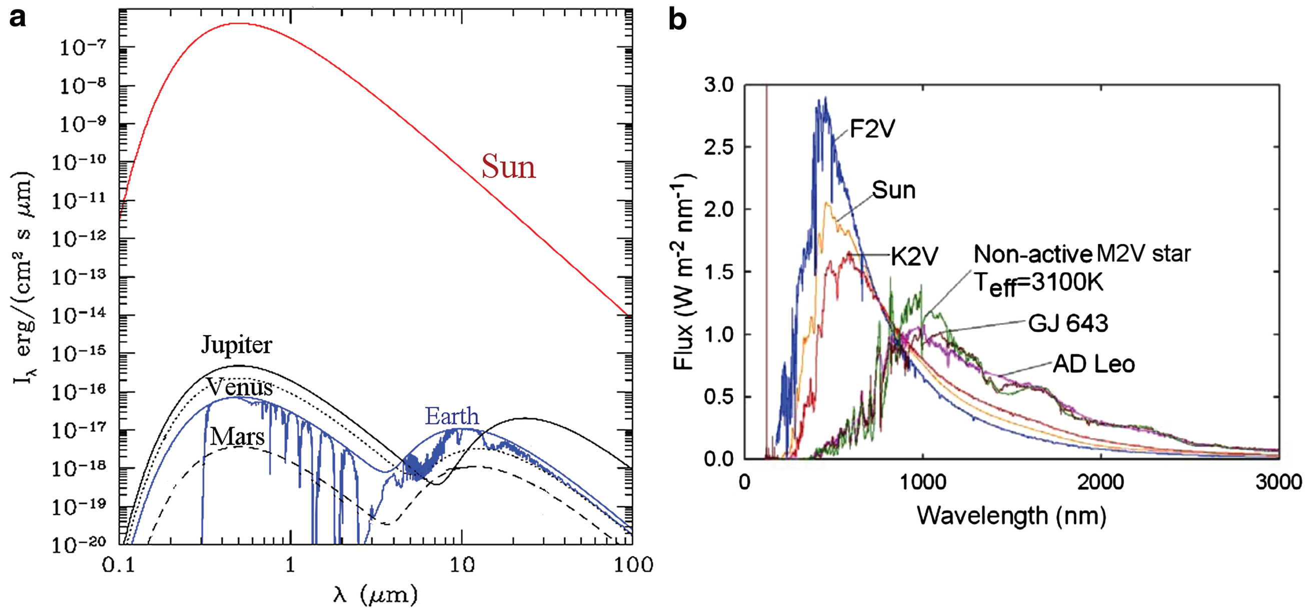


FIG. 1. (**a**) Smithsonian Astrophysical Observatory model of our Solar System (assumed here to be blackbodies with Earth spectrum shown). (**b**) Spectra of different host stars (Segura *et al.*, 2005). Color images available online at www.liebertonline.com/ast.

space-based missions (Darwin, Terrestrial Planet Finder, New World Observer).

In the next year, space missions like CoRoT (Centre National d'Études Spatiales) (Rouan *et al.*, 1998) and Kepler (NASA) (Borucki *et al.*, 1997) will give us statistics on the number, size, period, and orbital distance of planets, from gas giants extending to terrestrial planets on the lower-mass-range end, as a first step to characterizing other rocky planets. Future space missions will be designed to characterize the planets' atmospheres. After a decade rich in giant exoplanet detections, indirect ground-based observation techniques have advanced to a level where we now have the capability to find planets of less than $10\,M_{\mathrm{Earth}}$ (so-called "super Earths"), which may be habitable, around small stars (see *e.g.*, Valencia *et al.*, 2006; Mayor *et al.*, 2009). These planets can be characterized with future space missions.

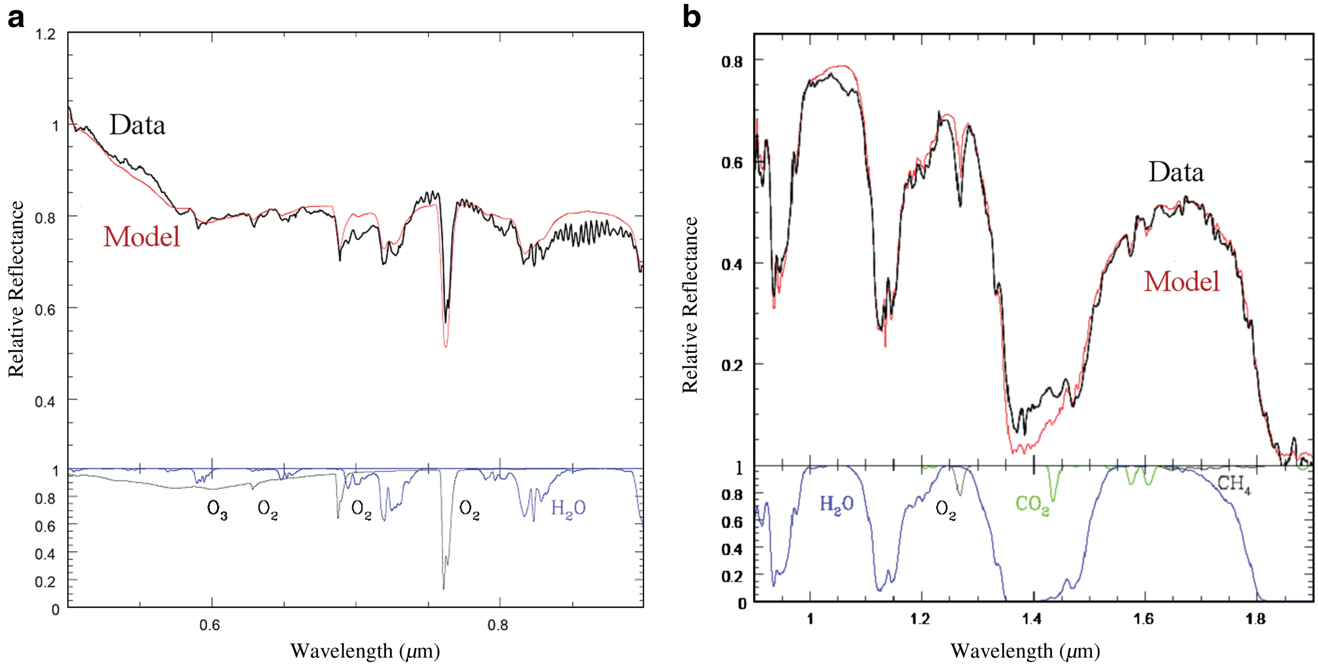
The current status of exoplanet characterization includes a surprisingly diverse set of giant planets. For a subset of these planets, some properties have been measured or inferred via observations of the host star, a background star, or the combination of the stellar and planetary photons (radial velocity, microlensing, transits, and astrometry). These observations have yielded measurements of planetary mass, orbital elements, and (for transits) the planetary radius. In recent years, physical and chemical characteristics of the upper atmospheres of some of the transiting planets have been identified. Specifically, observations of transits, combined with radial velocity information, have provided estimates of the mass and radius of the planets (see, *e.g.*, Torres *et al.*, 2008), planetary brightness temperature (Charbonneau *et al.*, 2005; Deming *et al.*, 2005), planetary day-night temperature difference (Harrington *et al.*, 2006; Knutson *et al.*, 2007), and even absorption features of giant planetary upper-atmospheric constituents: sodium (Charbonneau *et al.*, 2002), hydrogen (Vidal-Madjar *et al.*, 2004), water (Tinetti *et al.*, 2007), methane, carbon monoxide, and carbon dioxide (see, *e.g.*, Grillmair *et al.*, 2008; Swain *et al.*, 2009). The first imaged exoplanetary candidates around young stars show the improvement in direct detection techniques that are designed to resolve the planet and collect its photons. This can currently be achieved for widely separated young objects and has already detected exoplanetary candidates (see, *e.g.*, Kalas *et al.*, 2008; Marois *et al.*, 2008; Lagrange *et al.*, 2009). Future space missions will have the explicit purpose of detecting other Earth-like worlds, analyzing their characteristics, determining the composition of their atmospheres, investigating their capability to sustain life as we know it, and searching for signs of life. They will also have the capacity to investigate the physical properties and composition of a broader diversity of planets to aid in our understanding of the formation of planets and interpretation of potential biosignatures. Figure 2 shows the detectable features in a planet's reflection, emission, and transmission spectrum with the use of Earth as a proxy.

In this paper, we discuss how we can read a planet's spectral fingerprint and characterize whether it is potentially habitable. In Section 2, we discuss the first steps to detect a habitable planet and set biomarker* detection in context. Section 3 focuses on low-resolution biomarkers in the spectrum of an Earth-like planet, and in Section 4 we discuss spectral evolution of a habitable planet, cryptic worlds, abiotic sources of biomarkers, and Earth's spectra around different host stars. Section 5 summarizes the article.

2. Characterizing a Habitable Planet

A planet is a very faint, small object close to a very bright and large object, its parent star. In the visible part of the spectrum, we observe the starlight, reflected off the planet; in

*The term biomarker is used here to mean detectable atmospheric species or set of species whose presence at significant abundance strongly suggests a biological origin.



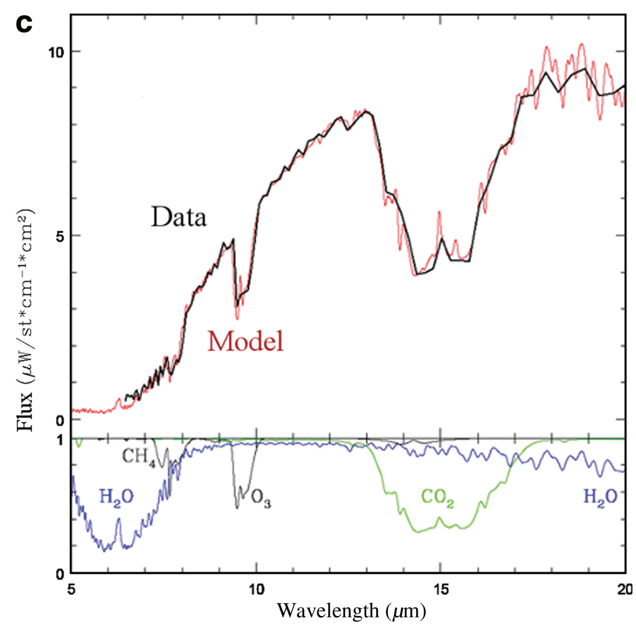


FIG. 2. Observed reflectivity spectrum in the visible (**a;** Woolf *et al.,* 2002), near IR (**b;** Turnbull *et al.,* 2006), and emission spectrum in the IR (**c;** Christensen and Pearl, 1997) of the integrated Earth, as determined from Earthshine and space, respectively. The data is shown in black and the Smithsonian Astrophysical Observatory model in red. The reflectivity scale is arbitrary. Color images available online at www.liebertonline.com/ast.

the IR, we detect the planet's own emitted flux. The Earth-Sun intensity ratio is about 10^{-7} in the thermal IR ($\sim 10\,\mu$m) and about 10^{-10} in the visible ($\sim 0.5\,\mu$m) (see Fig. 1), but the contrast ratio of a hot giant exoplanet to its parent star's flux as well as the contrast ratio of a planet to a smaller parent star is much more favorable, which makes Earth-like planets around small stars very interesting targets. The spectrum of the planet can contain signatures of atmospheric species, which create its spectral fingerprint. The trade-off between contrast ratio and space-based mission design, not discussed here, has lead to several different space mission concepts that are currently under detailed study.

Figure 2 shows observations and model fits to spectra of Earth in three wavelength ranges (Kaltenegger *et al.,* 2007). The data shown in Fig. 2 (on the left) is the visible Earthshine spectrum (Woolf *et al.,* 2002), in the center is the near-IR Earthshine spectrum (Turnbull *et al.,* 2006), and on the right is the thermal infrared spectrum of Earth as measured by a spectrometer en route to Mars (Christensen and Pearl, 1997). The data are shown in black; the Smithsonian Astrophysical Observatory model is shown in red. In each case, the constituent gas spectra in a clear atmosphere are shown in the bottom panel, for reference.

The interferometric systems design operates in the mid-IR (6–20 μm) and observes the thermal emission emanating from the planet. The coronagraph and occulter concepts detect the reflected light of a planet and operate in the visible and in the near IR (0.5–1 μm). The viewing geometry results

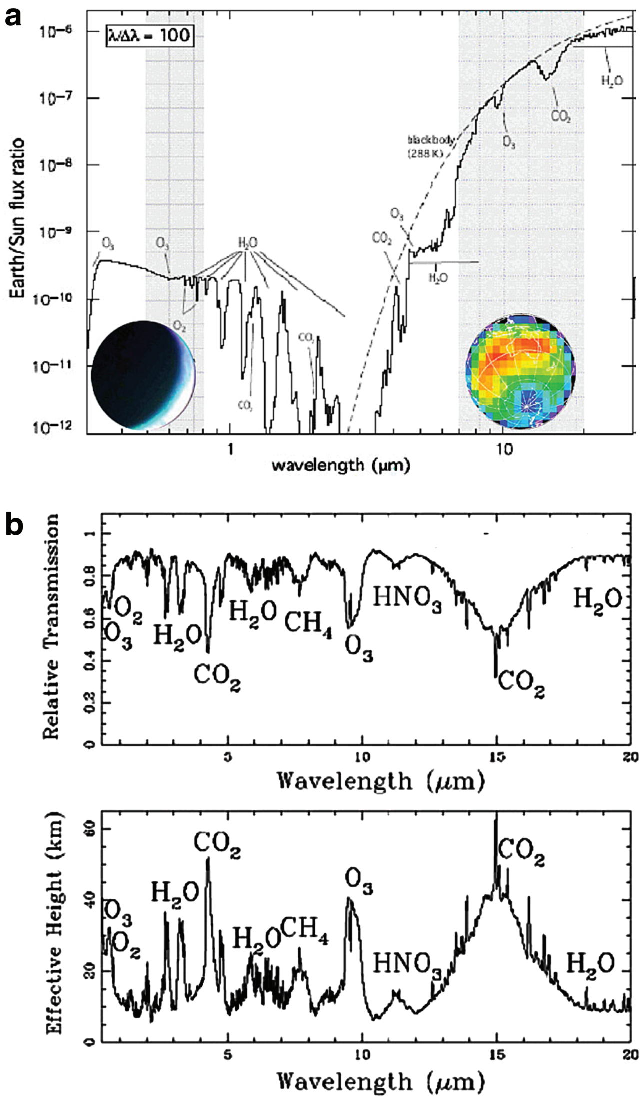


FIG. 3. Synthetic reflection and emission spectra (**a**) and transmission spectra (**b**) of Earth from UV to IR is shown. The intensity is given as a fraction of solar intensity as well as the relative height in the atmosphere. The atmospheric features are indicated. Color images available online at www.liebertonline.com/ast.

in different flux contribution of the overall detected signal from the bright and dark side, the reflected light, and the planet's hot and cold regions for the emitted flux. Both spectral regions contain the signature of atmospheric gases that may indicate habitable conditions and, possibly, the presence of a biosphere: CO_2, H_2O, O_3, CH_4, and N_2O in the thermal IR and H_2O, O_3, O_2, CH_4, and CO_2 in the visible to near IR. The presence or absence of these spectral features (detected individually or collectively) will indicate similarities or differences for the atmospheres of terrestrial planets, as well as astrobiological potential [see Fig. 3; see Pallé *et al.* (2009) and Kaltenegger and Traub (2009) for details on Earth's transmission spectrum].

Our search for signs of life is based on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth, in that it requires liquid water as a solvent and has a carbon-based chemistry (see, *e.g.*, Brack, 1993; Des Marais *et al.*, 2002). Life based on a different chemistry is not considered here because such life-forms, should they exist, would produce signatures in their atmospheres that are so far unknown. We assume, therefore, that there is the potential for the existence of extraterrestrial life that is similar to life on Earth, in that it would involve the same input and output gases and exist out of thermodynamic equilibrium (Lovelock, 1975). Biomarkers are used here to mean detectable species, or a set of species, whose presence at significant abundance strongly suggests a biological origin [*e.g.*, couple $CH_4 + O_2$, or $CH_4 + O_3$ (Lovelock, 1975)]. Bioindicators are indicative of biological processes but can also be produced abiotically. It is their quantities and detection, along with other atmospheric species, all within a certain context (for instance, the properties of the star and the planet) that point toward a biological origin.

2.1. Characterizing a planetary environment

It is relatively straightforward to ascertain remotely that Earth is a habitable planet, replete with oceans, a greenhouse atmosphere, global geochemical cycles, and life—that is, if one has data with arbitrarily high signal-to-noise ratio (S/N) and spatial and spectral resolution. The interpretation of observations of other planets with limited S/N and spectral resolution, as well as absolutely no spatial resolution (as envisioned for the first-generation instruments) will be far more challenging, the implication of which is that we need to gather information on the planetary environment to understand what we will see.

The following step by step approach can be taken to set the planetary atmosphere into context. After detection, investigators will focus on main properties of the planetary system, its orbital elements, and the presence of an atmosphere with use of the light curve of the planet and a crude estimate of the planetary nature with very low-resolution information (three or four channels). Then a higher-resolution spectrum will be used to identify the compounds of the planetary atmosphere and constrain the temperature and radius of the observed exoplanet. In that context, investigators will attempt to discern whether an abiotic explanation of all compounds seen in the atmosphere of such a planet is possible. If no such explanation can be put forth, a biotic hypothesis will be considered. O_2, O_3, and CH_4 are good biomarker candidates that can be detected by a low-resolution (resolution < 50) spectrograph. Note that, if the presence of biogenic gases such as $O_2/O_3 + CH_4$ implies the potential for a massive and active biosphere, their absence does not imply the absence of life. Life existed on Earth before the interplay between oxygenic photosynthesis and before carbon cycling produced an oxygen-rich atmosphere.

2.2. Temperature and radius of a planet

Knowing the surface temperature and the planetary radius is crucial for a general understanding of the physical and chemical processes that occur on a planet (tectonics, hydrogen loss to space). In theory, spectroscopy can provide some detailed information on the thermal profile of a planetary atmosphere. This requires, however, a spectral resolution and sensitivity that are well beyond the performance of a first-generation spacecraft. Here, we concentrate on the initially available observations.

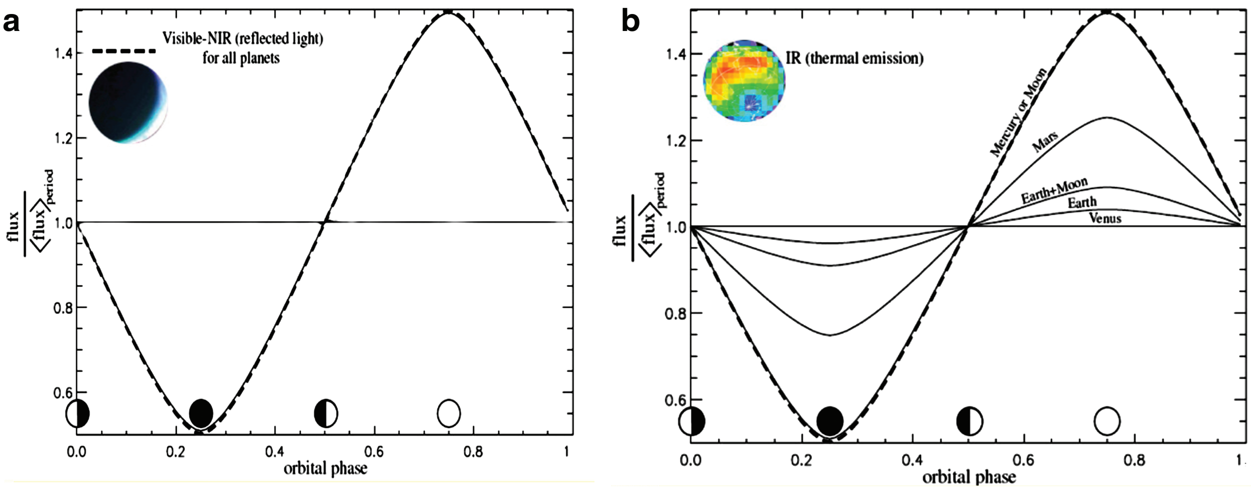


FIG. 4. Orbital light curve for blackbody planets in a circular orbit with null obliquities, with and without an atmosphere in the visible (**a**) and thermal infrared (**b**) (after Selsis, 2002). Color images available online at www.liebertonline.com/ast.

The stellar energy of a star, F_{star}, that is received at the measured orbital distance can be calculated. The surface temperature of the planet at this distance depends on its albedo and on the greenhouse warming by atmospheric compounds. However, with a low-resolution spectrum of the thermal emission, the mean effective temperature and the radius of the planet can be obtained. The ability to associate a surface temperature to the spectrum relies on the existence and identification of spectral windows probing the surface or the same atmospheric levels. Such identification is not trivial. For an Earth-like planet, there are some atmospheric windows that can be used in most of the cases, especially between 8 and 11 μm as seen in Fig. 3. This window, however, would become opaque at high H_2O partial pressure [*e.g.*, the inner part of the Habitable Zone (HZ) where a lot of water is vaporized] and at high CO_2 pressure (*e.g.*, a very young Earth or the outer part of the HZ).

The accuracy of the radius and temperature determination will depend on the quality of the fit (and thus on the sensitivity and resolution of the spectrum), the precision of the Sun-star distance, the cloud coverage, and the distribution of brightness temperatures over the planetary surface. Assuming the effective temperature of our planet were radiated from the uppermost cloud deck at about 12 km would introduce about 2% error on the derived Earth radius. For a transiting planet whose radius is known, the measured IR flux can directly be converted into a brightness temperature that will provide information on the temperature of the atmospheric layers responsible for the emission. If the mass of non-transiting planets can be measured (by radial velocity, astrometric observations, or both), an estimate of the radius can be made by assuming a bulk composition of the planet, which can then be used to convert IR fluxes into temperatures.

Important phase-related variations in a planet's flux are due to a high day/night temperature contrast and imply a low greenhouse effect and absence of a stable liquid ocean. Therefore, habitable planets can be distinguished from airless or Mars-like planets by the amplitude of the observed variations of mean brightness temperature, T_b. The orbital flux variation in the IR can distinguish planets with and without an atmosphere in the detection phase (see also Selsis, 2002; Gaidos and Williams, 2004). Strong variation of the thermal flux with the phase reveals a strong difference in temperature between the day and night hemisphere of the planet, a consequence of the absence of a dense atmosphere. In such a case, estimating the radius from the thermal emission is difficult because most of the flux received comes from the small and hot substellar area. The ability to retrieve the radius would depend on assumptions that can be made on the orbit geometry and the rotation rate of the planet. In most cases, degenerate solutions will exist. When the mean brightness temperature is stable along the orbit, the estimated radius is more reliable. The radius can be measured at different points of the orbit and thus for different values of T_b, which should allow for an estimate of the error.

Note that also a Venus-like exoplanet would exhibit nearly no measurable phase-related variations of its thermal emission due to the fast rotation of its atmosphere and its strong greenhouse effect. Such a planet could only be distinguished as nonhabitable via spectroscopy. The mean value of T_b estimated over an orbit can be used to estimate the albedo of the planet, A, through the balance between the incoming stellar radiation and the outgoing IR emission.

The thermal light curve (*i.e.*, the integrated IR emission measured at different positions on the orbit) exhibits smaller variations, due to the phase (whether the observer sees mainly the dayside or the nightside) and to the season for a planet with an atmosphere, than the corresponding visible light curve (see Fig. 4). In the visible ranges, the reflected flux allows us to measure the product $A \times R^2$, where R is the planetary radius (a small, but reflecting, planet appears as bright as a big but dark planet). The first generation of optical instruments will be very far from the angular resolution required to measure an exoplanetary radius directly.

Presently, radius measurements can only be performed by an accurate photometric technique when the planet transits in front of its parent star. If the secondary eclipse of the transiting planet can be observed (when the planet passes behind the star), then the thermal emission of the planet can be measured, which, because the radius is known from the primary transit, allows for the retrieval of T_b. If a non-transiting target is observed in both visible and IR ranges, the

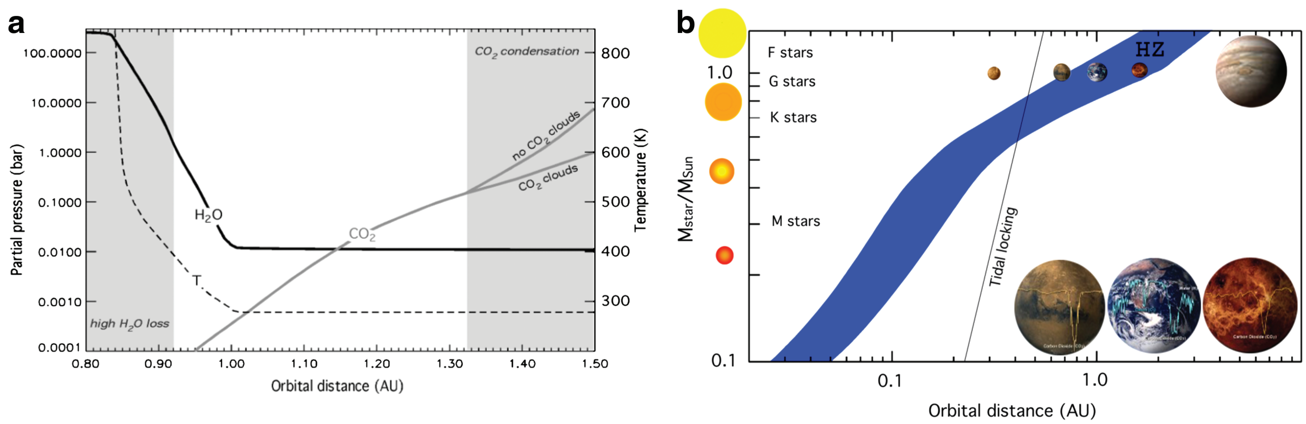


FIG. 5. (**a**) Surface conditions on a habitable planet within the HZ (data adapted from Kasting *et al.*, 1993; Forget and Pierrehumbert, 1997; Kaltenegger and Selsis, 2007) and (**b**) the HZ as a function of stellar type. Color images available online at www.liebertonline.com/ast.

albedo can be estimated in the visible once the radius is inferred from the IR spectrum and can be compared with one derived from the thermal emission only.

3. Habitable Planets

The circumstellar HZ is defined as the region around a star within which starlight is sufficiently intense to maintain liquid water at the surface of the planet without initiating runaway greenhouse conditions that would vaporize the whole water reservoir and, as a second effect, include the photodissociation of water vapor and the loss of hydrogen to space [see, *e.g.*, Kasting *et al.* (1993), Kasting (1997), Selsis (2000), for detailed discussion]. The semimajor axis in the middle of the HZ a(HZ, AU), is derived by scaling the Earth-Sun system and using $L_{star}/L_{Sun} = (R_{star}/R_{Sun})^2\ (T_{star}/T_{Sun})^4$, so $a_{HZ} = 1$ AU $(L_{star}/L_{Sun})^{0.5}$, and finally

$$a_{HZ} = 1\ \mathrm{AU} \times [(L/L_{Sun})/S_{eff}]^{0.5}$$

This formula assumes that the planet has a similar albedo to Earth, that it rotates or redistributes the insolation as on Earth, and that it has a similar greenhouse effect. S_{eff} is 1.90, 1.41, 1.05, and 1.05 for F, G, K, and M stars, respectively, for the inner edge of the HZ (where runaway greenhouse occurs) and 0.46, 0.36, 0.27, and 0.27 for F, G, K, and M stars, respectively, for the outer edge of the HZ (assuming a maximum greenhouse effect in the planet's atmosphere) (Kasting *et al.*, 1993). On an Earth-like planet where the carbonate-silicate cycle is at work, the level of CO_2 in the atmosphere depends on the orbital distance; CO_2 is a trace gas close to the inner edge of the HZ but a major compound in the outer part of the HZ (Forget and Pierrehumbert, 1997) (Fig. 5).

Earth-like planets close to the inner edge are expected to have a water-rich atmosphere or to have lost their water reservoir to space. This is one of the first theories that can be tested with a first-generation space mission. However, the limits of the HZ are known qualitatively more than quantitatively. This uncertainty is mainly due to the complex role of clouds and three-dimensional climatic effects not yet included in the modeling. Thus, planets slightly outside the computed HZ could still be habitable, while planets at habitable orbital distance may not be habitable because of their size or chemical composition. As the HZ is defined for surface conditions only, chemolithotrophic life, the metabolism of which does not depend on stellar light, can still exist outside the HZ and thrive in the interior of a planet where liquid water is available. Such metabolisms (at least those we know on Earth) do not produce O_2 and rely on very limited sources of energy (compared to stellar light) and electron donors (compared to H_2O on Earth). They mainly catalyze reactions that would occur at a slower rate in purely abiotic conditions, and they are thus not expected to modify a whole planetary environment in a detectable way.

3.1. Potential biomarkers

Owen (1980) suggested searching for O_2 as a tracer of life. Oxygen in high abundance is a promising bioindicator. Oxygenic photosynthesis, the by-product of which is molecular oxygen extracted from water, allows terrestrial plants and photosynthetic bacteria (cyanobacteria) to use abundant H_2O rather than to rely on scarce supplies of electron donors to reduce CO_2, like H_2 and H_2S. With oxygenic photosynthesis, the production of the biomass becomes limited only by nutriments and no longer by energy (light, in this case) or by the abundance of electron donors. Oxygenic photosynthesis at a planetary scale results in the storage of large amounts of radiative energy in chemical energy, in the form of organic matter. For this reason, oxygenic photosynthesis had a tremendous impact on biogeochemical cycles on Earth and eventually resulted in the global transformation of Earth's environment. Less than 1 ppm of atmospheric O_2 comes from abiotic processes (Walker, 1977). Cyanobacteria and plants are responsible for this production by using solar photons to extract hydrogen from water and using the hydrogen to produce organic molecules from CO_2. This metabolism is called oxygenic photosynthesis. The reverse reaction, the use of O_2 to oxidize the organics produced by photosynthesis, can occur abiotically when organics are exposed to free oxygen or biotically by eukaryotes breathing O_2 and consuming organics. Because of this balance, the net release of O_2 in the atmosphere is due to the burial of organics in sediments. Each reduced carbon buried results in a

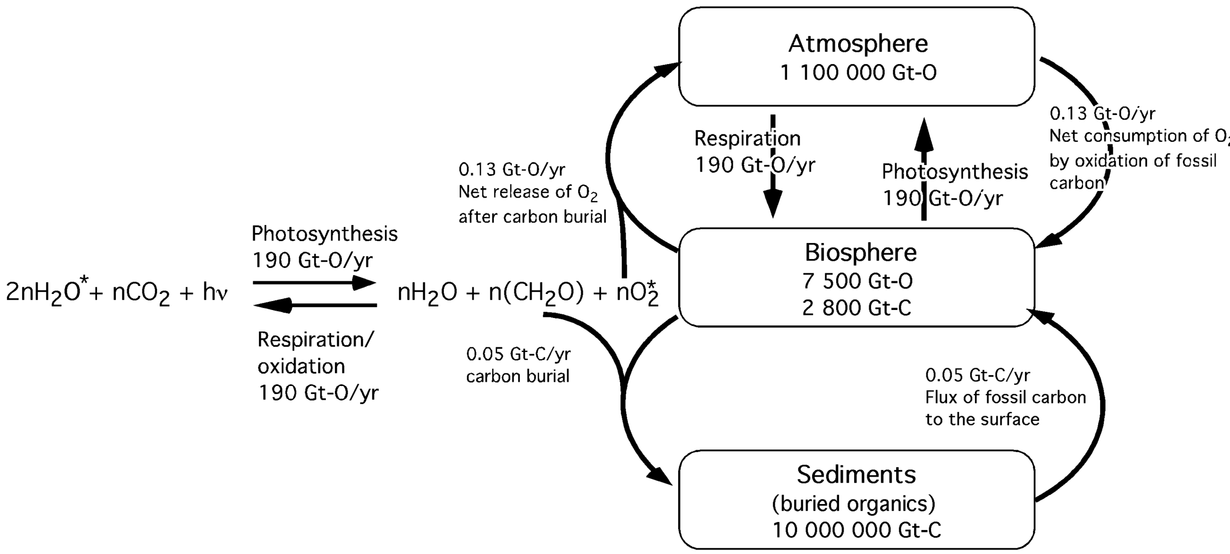


FIG. 6. Oxygen cycle on Earth (Kaltenegger and Selsis, 2007).

free O_2 molecule in the atmosphere. This net release rate is also balanced by weathering of fossilized carbon when exposed to the surface (see Fig. 6). The oxidation of reduced volcanic gases, such as H_2 and H_2S, also accounts for a significant fraction of the oxygen losses. The atmospheric oxygen is recycled through respiration and photosynthesis in less than 10,000 years. In the case of a total extinction of Earth's biosphere, the atmospheric O_2 would disappear in a few million years.

Reduced gases and oxygen have to be produced concurrently to be detectable in an atmosphere, as they react rapidly with each other. Thus, the chemical imbalance traced by the simultaneous signature of O_2, O_3, or both and of a reduced gas like CH_4 can be considered a signature of biological activity (Lovelock, 1975). The spectrum of Earth has exhibited a strong IR signature of ozone for more than 2 billion years and a strong visible signature of O_2 for an undetermined period of time between 2 and 0.8 billion years (depending on the required depth of the band for detection and the actual evolution of the O_2 level) (Kaltenegger *et al.*, 2007). This difference is due to the fact that a saturated ozone band appears already at very low levels of O_2 (10^{-4} ppm), while the oxygen line remains unsaturated at values below 1 present atmospheric level (Segura *et al.*, 2003). In addition, the stratospheric warming decreases with the abundance of ozone, which makes the O_3 band deeper for an ozone layer less dense than that in the present atmosphere. The depth of the saturated O_3 band is determined by the temperature difference between the surface-cloud continuum and the ozone layer.

Nitrous oxide (N_2O) is produced in abundance by life but only in negligible amounts by abiotic processes. Nearly all of Earth's N_2O is produced by the activities of anaerobic denitrifying bacteria. N_2O would be hard to detect in Earth's atmosphere with low resolution, as its abundance is low at the surface (0.3 ppm by volume) and falls off rapidly in the stratosphere. Spectral features of N_2O would become more apparent in atmospheres with more N_2O or less H_2O vapor, or a combination of the two. Segura *et al.* (2003) calculated the level of N_2O for different O_2 levels and found that, though N_2O is a reduced species compared to N_2, its level decreases with O_2. This is due to the fact that a decrease in O_2 produces an increase in H_2O photolysis, which results in the production of more hydroxyl radicals (OH) responsible for the destruction of N_2O.

The methane found in the present atmosphere of Earth has a biological origin, except for a small fraction produced abiotically in hydrothermal systems where hydrogen is released by the oxidation of Fe by H_2O and reacts with CO_2 to form CH_4. Depending on the degree of oxidation of a planet's crust and upper mantle, such nonbiological mechanisms can also produce large amounts of CH_4 under certain circumstances. Therefore, the detection of CH_4 alone cannot be considered a sign of life, though its detection in an oxygen-rich atmosphere would be difficult to explain in the absence of a biosphere. Note that CH_4 on Mars, whose atmosphere contains 0.1% of O_2 and some O_3, may have been detected (Mumma *et al.*, 2009). In this case, the amounts involved are extremely low, and the origin of the martian O_2 and O_3 is known to have resulted from photochemical reactions initiated by the photolysis of CO_2 and water vapor. If confirmed, the presence of CH_4 could be explained by subsurface geochemical process, assuming that reducing conditions exist on Mars below the highly oxidized surface. The case of NH_3 is similar to that of CH_4. They are both released into Earth's atmosphere by the biosphere with similar rates, but the atmospheric level of NH_3 is orders of magnitude lower due to its very short lifetime under UV irradiation. The detection of NH_3 in the atmosphere of a habitable planet would thus be extremely interesting, especially if found with oxidized species.

The detection of H_2O and CO_2, though not as biosignatures themselves, is important in the search for signs of life because they are raw materials for life and thus necessary for planetary habitability.

There are other molecules that could, under some circumstances, act as excellent biomarkers, for example, the manufactured chlorofluorocarbons (CCl_2F_2 and CCl_3F) in our current atmosphere in the thermal IR waveband; but their abundances are too low to be spectroscopically observed at low resolution.

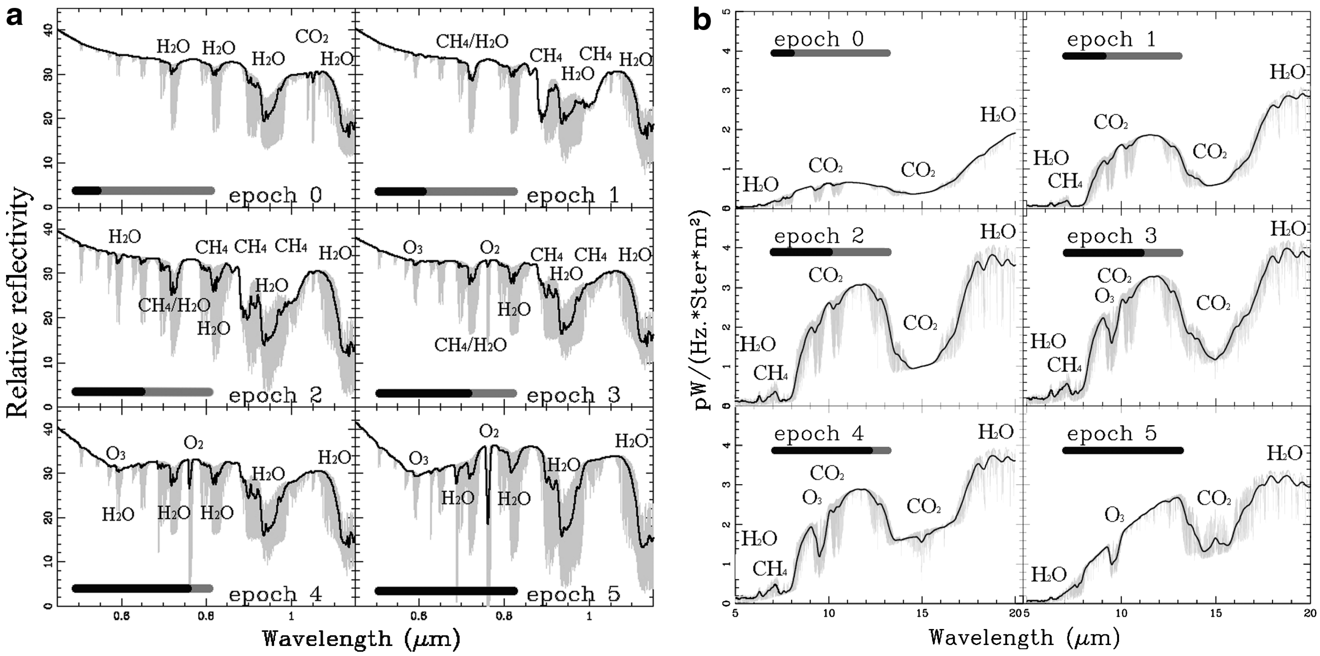


FIG. 7. The visible to near IR (**a**) and mid-IR (**b**) spectral features on an Earth-like planet change considerably over its evolution from a CO_2-rich atmosphere (epoch 0) to a CO_2/CH_4-rich atmosphere (epoch 3) to a present-day atmosphere (epoch 5). The bold lines show spectral resolution of 80 and 25 comparable to the proposed visible Terrestrial Planet Finder and Darwin/Terrestrial Planet Finder Interferometer mission concept, respectively.

3.1.1. Low-resolution spectral information in the visible to near IR. In the visible to near IR, increasingly strong H_2O bands can be seen at 0.73 μm, 0.82 μm, 0.95 μm, and 1.14 μm. The strongest O_2 feature is the saturated Frauenhofer A-band at 0.76 μm. A weaker feature at 0.69 μm cannot be seen with low resolution (see Fig. 3). O_3 has a broad feature, the Chappuis band, which appears as a broad triangular dip in the middle of the visible spectrum from about 0.45 μm to 0.74 μm. The feature is very broad and shallow. Methane, at present terrestrial abundance (1.65 ppm), has no significant visible absorption features; but, at high abundance, it has strong visible bands at 0.88 μm and 1.04 μm, which are readily detectable, for example, in early Earth models (see Fig. 7). CO_2 has negligible visible features at present abundance; but in a high-CO_2 atmosphere of 10% CO_2, as would have been the case for an early Earth evolution stage, the weak 1.06 μm band could be observed. In the UV, O_3 shows a strong feature, though this is not discussed here. The red edge of land plants developed about 0.44 Ga. It could be observed on a cloudless Earth or in the event that the cloud pattern is known (see Section 4).

3.1.2. Low-resolution spectral information in the mid-IR. In the mid-IR on Earth, the detectable signatures of biological activity in low resolution are the combined detection of the 9.6 μm O_3 band, the 15 μm CO_2 band, and the 6.3 μm H_2O band or its rotational band that extends from 12 μm out into the microwave region (Selsis, 2002). The 9.6 μm O_3 band is highly saturated and thus a poor quantitative indicator, but it is an excellent qualitative indicator for the existence of even traces of O_2. CH_4 is not readily identified via low-resolution spectroscopy for present-day Earth, but the methane feature at 7.66 μm in the IR is easily detectable at higher abundances [see, *e.g.,* 100× on early Earth (Kaltenegger *et al.,* 2007)] provided, of course, that the spectrum contains the whole band and a high enough S/N. Taken together with molecular oxygen, abundant CH_4 can indicate biological processes (see also Sagan *et al.,* 1993; Segura *et al.,* 2003). Although methane's abundance is less than 1 ppm in Earth's atmosphere, the 7.75 μm shows up in a medium resolution (Res = 100) IR spectrum. Three N_2O features in the thermal IR are detectable at 7.75 μm and 8.52 μm, and at 16.89 μm for levels higher than in the present atmosphere of Earth.

4. Geological Evolution, Cryptic Worlds, Abiotic Sources, and Host Stars

4.1. Evolution of biomarkers over geological times on Earth

One crucial factor in interpreting planetary spectra is the point in the evolution of the atmosphere when biomarkers and habitability become detectable.

The spectrum of Earth has not been static throughout the past 4.5 Ga. This is due to the variations in the molecular abundances, the temperature structure, and the surface morphology over time. At about 2.3 Ga, oxygen and ozone became abundant, which affected the atmospheric absorption component of the spectrum. At about 0.44 Ga, an extensive land plant cover followed, which generated the red chlorophyll edge in the reflection spectrum. The composition of the surface (especially in the visible), the atmospheric composition, and the temperature-pressure profile can all have a significant influence on the detectabilty of a signal. Figure 7 shows theoretical visible and mid-IR spectra of the Earth at six epochs during its geological evolution (Kaltenegger *et al.,* 2007). The epochs are chosen to represent major developmental stages of the Earth and life on Earth. If an extrasolar planet is found with a corresponding spectrum, the stages of evolution of our planet can be used to characterize it in terms of habitability and the degree to which it shows signs of life. Furthermore, we can learn about the evolution of our own planet's atmosphere and possibly the emergence of life by observing exoplanets in different stages of their evolution. Earth's atmosphere has experienced dramatic evolution over 4.5 billion years, and other planets may exhibit similar or greater evolution, and at different rates. It shows epochs that reflect significant changes in the chemical composition of the atmosphere. The oxygen and ozone absorption features could have been used to indicate the presence of biological activity on Earth anytime during the past 50% of the age of the Solar System. Different signatures in the atmosphere are clearly visible over Earth's evolution and observable with low resolution.

The use of theoretical model spectra of Earth to explore temperature sensitivity (hot house and cold scenario) (*e.g.,* Pavlov *et al.,* 2000; Schindler and Kasting, 2000; Traub and Jucks, 2002) and consideration of spectra that would be detected over the course of the evolution of life on Earth (Kaltenegger *et al.,* 2007) have resulted in a variety of spectral fingerprints that, theoretically, apply to our own planet [see also Grenfell *et al.,* 2010 (this volume)]. Those spectra will be used as part of a big grid to characterize any exoplanets found and will influence the design requirements for a spectrometer to detect habitable planets (Kaltenegger *et al.,* 2007).

4.2. Abiotic sources of biomarkers

Abiotic sources of biomarkers are very important to assess so that a "false positive" for life can be identified. CH_4 is an abundant constituent of the cold planetary atmospheres in the outer Solar System. On Earth, it is produced abiotically in hydrothermal systems where H_2 (produced from the oxidation of Fe by water) reacts with CO_2 in a certain range of pressures and temperatures. In the absence of atmospheric oxygen, abiotic CH_4 could build up to detectable levels. Therefore, the detection of CH_4 cannot be attributed unambiguously to life.

Oxygen (O_2) also has abiotic sources, the first of which is the photolysis of CO_2, followed by recombination of O atoms to form O_2 ($O + O + M \rightarrow O_2 + M$); a second source is the photolysis of H_2O followed by escape of hydrogen to space. The first source is a steady state maintained by stellar UV radiation but with a constant elemental composition of the atmosphere; the second source is a net supply of oxygen. To reach detectable levels of O_2 (in the reflected spectrum), the photolysis of CO_2 has to occur in the absence of outgassing of reduced species and in the absence of liquid water because of the wet deposition of oxidized species. Normally, the detection of the water vapor bands simultaneously with the O_2 band can rule out this abiotic mechanism (Segura *et al.,* 2007), though one should be careful, as the vapor pressure of H_2O over a high-albedo icy surface might be high enough to produce detectable H_2O bands. In the IR, this process cannot produce a detectable O_3 feature (Selsis *et al.,* 2002). The loss of hydrogen to space can result in massive oxygen leftovers; more than 200 bars of oxygen could build up after the loss of the hydrogen contained in Earth's oceans. However, the case of Venus tells us that such leftover oxygen has a limited lifetime in the atmosphere (because of the oxidation of the crust and the loss of oxygen to space). We do not find O_2 in the venusian atmosphere despite the massive loss of water that probably occurred in the early history of the planet. Also, such evaporation-induced build-up of O_2 should occur only when a planet is closer to a certain distance from the star, and it should affect small planets with low gravity more dramatically. For small planets ($<0.5\,M_{\mathrm{Earth}}$) close to the inner edge of the HZ (<0.93 AU from the present Sun), there is a risk of abiotic oxygen detection, but this risk becomes negligible for big planets that are farther away from their star. On Earth, the fact that oxygen and, indirectly, ozone are by-products of biological activity does not mean that life is the only process able to enrich an atmosphere with these compounds. The question of the abiotic synthesis of biomarkers is crucial, but few studies have been dedicated to the topic (Léger *et al.,* 1993; Rosenqvist and Chassefiere, 1995; Selsis *et al.,* 2002; Lagrange *et al.,* 2009).

4.3. Cryptic worlds, surface features, vegetation features, and cloud features

While they efficiently absorb the visible light, photosynthetic plants have developed strong IR reflection (possibly as a defense against overheating and chlorophyll degradation), which results in a steep change in reflectivity around 700 nm, called the red edge. The primary molecules that absorb the energy and convert it to drive photosynthesis (H_2O and CO_2 into sugars and O_2) are chlorophyll *a* (0.450 μm) and *b* (0.680 μm). The exact wavelength and strength of the spectroscopic "vegetation red edge" (VRE) depends on the plant species and environment. Around 440 million years ago (Schopf, 1993; Pavlov *et al.,* 2003), an extensive land plant cover developed on Earth that generated the red chlorophyll edge in the reflection spectrum between 700 and 750 nm. Averaged over a spatially unresolved hemisphere of Earth, the additional reflectivity of this spectral feature is typically only a few percent (see also (Montañés-Rodriguez *et al.,* 2005; Kaltenegger and Traub, 2009). Several groups (Christensen and Pearl, 1997; Arnold *et al.,* 2002; Woolf *et al.,* 2002; Turnbull *et al.,* 2006; Montañés-Rodriguez *et al.,* 2007) have measured the integrated Earth spectrum via the technique of Earthshine, using sunlight reflected from the non-illuminated, or "dark," side of the Moon. Earthshine measurements have shown that detection of Earth's VRE is feasible if the resolution is high and the cloud coverage is known, but such measurements are difficult, owing to the VRE's broad, essentially featureless spectrum and cloud coverage. Our knowledge of the reflectivity of different surface components on Earth—such as deserts, oceans, and ice—helps in assigning the VRE of the Earthshine spectrum to terrestrial vegetation.

By picking the most different reflecting surfaces (snow with a high albedo and sea with an extremely low albedo), we show in Fig. 8 the maximum effect surface coverage could have on the amount of light reflected from an exoplanet—assuming the whole planet surface is covered with that one material, the surface area is the same, and also artificially assuming similar cloud coverage and atmosphere for comparison.

Earth's hemispherical integrated VRE signature is very weak, but planets with different rotation rates, obliquities,

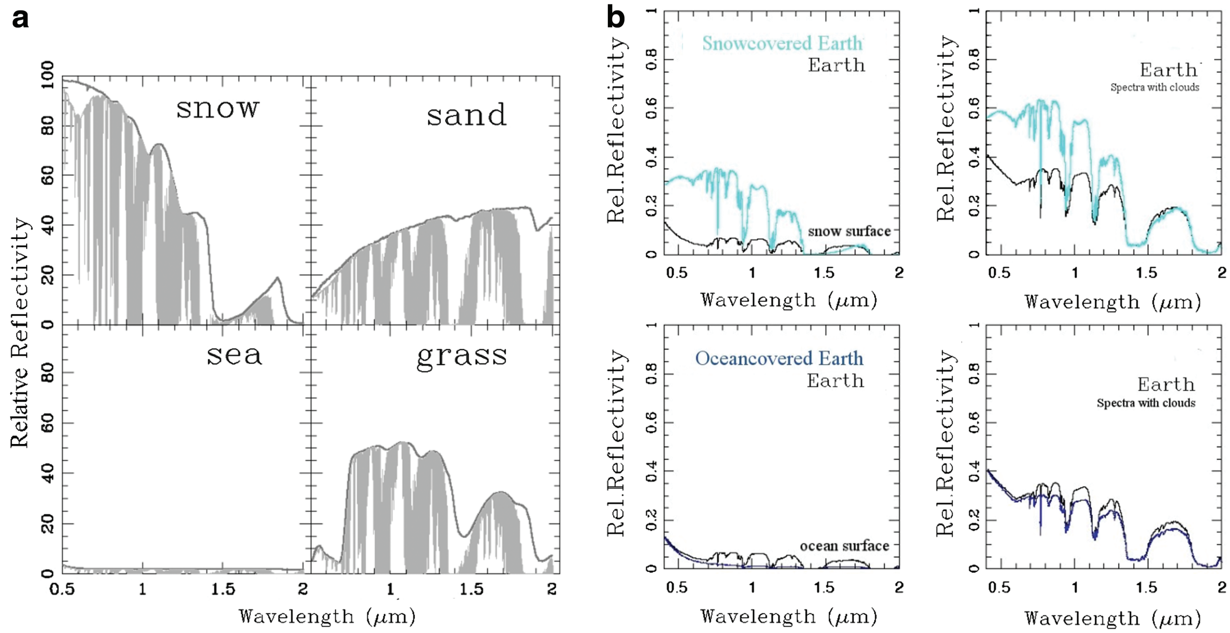


FIG. 8. (**a**) Reflectivity of different surfaces for present-day cloud-free Earth atmosphere. (**b**) Spectra of present-day Earth with a total ocean and snow cover without (left) and with (right) clouds for a disk-averaged view. Note that the low albedo of the ocean reduces the overall flux while the high albedo of snow reflects more sunlight off the planet's surface. Color images available online at www.liebertonline.com/ast.

land-ocean fractions, and continental arrangements may have lower cloud cover and higher vegetated fraction (see, *e.g.*, Seager and Ford, 2002). Knowing that other pigments exist on Earth and that some minerals can exhibit a similar spectral shape around 750 nm (Seager *et al.*, 2005), the detection of the red edge of the chlorophyll on exoplanets, despite its interest, will not be unambiguous. Assuming that similar photosynthesis would evolve on a planet around other stellar types, possible different types of spectral signature have been modeled (Tinetti *et al.*, 2006) that could be a guide to interpreting other spectral signatures. Those signatures will be difficult to verify as biological in origin through remote observations.

On Earth, photosynthetic organisms are responsible for the production of nearly all the oxygen in the atmosphere. However, in many regions on Earth, and particularly where surface conditions are extreme—for example, in hot and cold deserts—photosynthetic organisms can be driven into and under substrates where light is still sufficient for photosynthesis. These communities exhibit no detectable surface spectral signature. The same is true of the assemblages of photosynthetic organisms at more than a few meters depth in water bodies. These communities are widespread and dominate local photosynthetic productivity. Figure 9 shows known cryptic photosynthetic communities and their calculated disk-averaged spectra of such hypothetical cryptic photosynthesis worlds. Such a world would be an Earth analogue except it would not exhibit a biological surface feature in the disc-averaged spectrum (Cockell *et al.*, 2009).

Another topic that has been proposed to discover continents and seas on an exoplanet is the daily variation of the

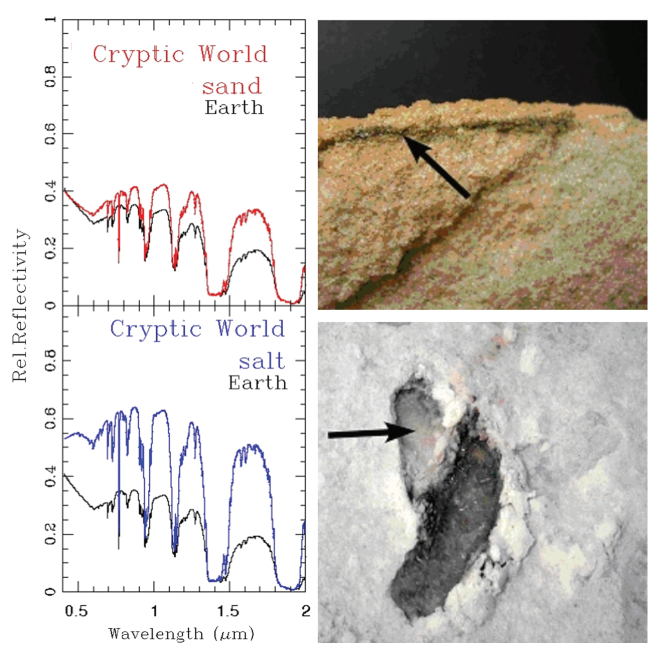


FIG. 9. Two examples of spectra of land-based cryptic photosynthetic communities. (**top**) A cryptoendolithic lichen (*arrow*) inhabiting the interstices of sandstone in the Dry Valleys of the Antarctic, (**bottom**) endoevaporites inhabiting a salt crust visible as pink pigmentation (*arrow*) (photo: Marli Bryant Miller), and their respective calculated clear reflection spectra. Substrates represent typical habitats for different cryptic biota (Cockell *et al.*, 2009). Color images available online at www.liebertonline.com/ast.

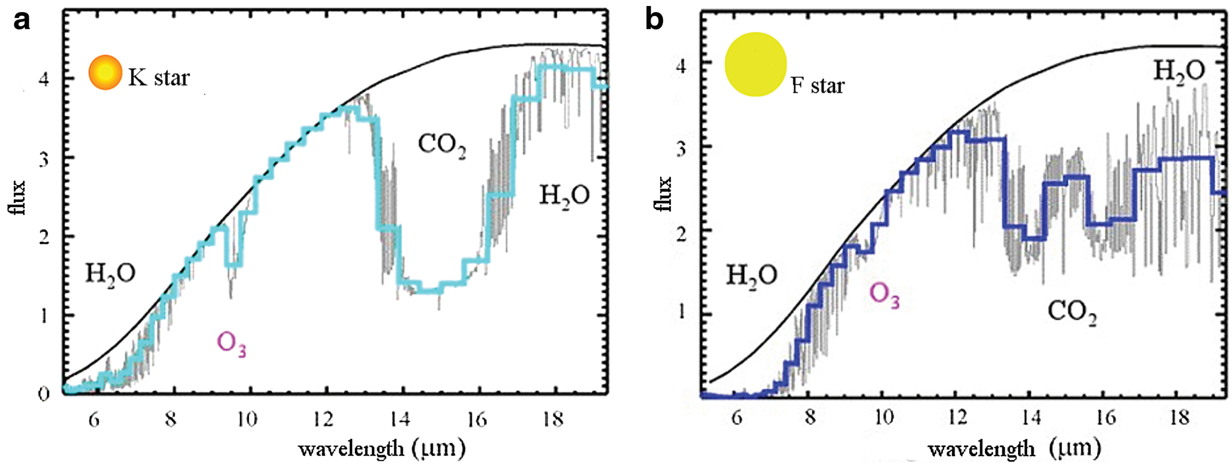


FIG. 10. Calculated IR spectrum of an Earth analogue with resolution of 30 around a F star (**a**) and K star (**b**) (Selsis, 2002). Color images available online at www.liebertonline.com/ast.

surface albedo in the visible (Ford *et al.*, 2001; Seager and Ford, 2002; Pallé *et al.*, 2008). On a cloud-free Earth, the diurnal flux variation in the visible caused by different surface features rotating in and out of view could be high, assuming hemispheric inhomogeneity. When the planet is only partially illuminated, a more concentrated signal from surface features could be detected as they rotate in and out of view on a cloudless planet (William and Gaidos, 2008). Earth has an average of 60% cloud coverage, which prevents easy identification of features without knowing the cloud distribution. Clouds are an important component of exoplanetary spectra because their reflection is high and relatively flat with wavelength. Clouds reduce the relative depths, full widths, and equivalent widths of spectral features, which weakens the spectral lines in both the thermal IR and visible (Kaltenegger *et al.*, 2007). In the thermal IR, clouds emit at temperatures that are generally colder than the surface, while in the visible the clouds themselves have a different spectrally dependent albedo that further influences the overall shape of the spectrum.

If the planet's signal could be recorded with a very high time resolution (a fraction of the rotation period of the planet) and S/N, the overall contribution of clouds to the signal could be determined (Pallé *et al.*, 2008; Cowan *et al.*, 2009). During each of these individual measurements, enough photons would have to be collected for a high individual S/N per measurement in order to correlate the measurements to the surface features, which is what precludes this method for first-generation missions that will observe a minimum of several hours to achieve a S/N of 5 to 10. For Earth (Pallé *et al.*, 2008; Cowan *et al.*, 2009); these measurements show a correlation to Earth's surface feature because the individual measurements are time resolved as well as have an individual high S/N, making it a very interesting concept for future generations of missions.

4.4. Influence of host stars

The range of characteristics of planets is likely to exceed, by far, our experience with the planets and satellites in our own Solar System. Models of planets more massive than our Earth—rocky super Earths—need to take into consideration the changing atmospheric structure as well as the interior structure of the planet (see, *e.g.*, Valencia *et al.*, 2006; Seager *et al.*, 2007). Also, Earth-like planets orbiting stars of different spectral type might evolve differently (Selsis, 2000; Segura *et al.*, 2003, 2005). Modeling these influences will help to optimize the design of the proposed instruments to search for Earth-like planets. The spectral resolution required for optimal detection of habitability and biosignatures must allow for detection of features on other planets that are similar to those on our own planet throughout Earth's evolution.

Using a numerical code that simulates the photochemistry of a wide range of planetary atmospheres, several groups (Selsis, 2000; Segura *et al.*, 2003, 2005; Paillet, 2006; Grenfell *et al.*, 2007) have simulated a replica of our planet orbiting different types of star: an F-type star (more massive and hotter than the Sun) and a K-type star (smaller and cooler than the Sun). The models assume the same background composition of the atmosphere as well as the strength of biogenic sources.

A planet orbiting a K star has a thin O_3 layer, compared to that of Earth, but still exhibits a deep O_3 absorption; indeed, the low UV flux is absorbed at lower altitudes than on Earth, which results in a less efficient warming (because of the higher heat capacity of the dense atmospheric layers). Therefore, the ozone layer is much colder than the surface, and this temperature contrast produces a strong feature in the thermal emission. The process works the other way around in the case of an F-type host star. Here, the ozone layer is denser and warmer than the terrestrial one, which exhibits temperatures about as high as the surface temperature. Thus, the resulting low temperature contrast produces only a weak and barely detectable feature in the IR spectrum. This comparison shows that planets orbiting G- (solar) and K-type stars may be better candidates for the search for the O_3 signature than planets orbiting F-type stars (see Fig. 10). This result is promising since G- and K-type stars are much more numerous than F-type stars, the latter being rare and affected by a short lifetime (less than 1 billion years).

5. Summary

Any information we collect on habitability is important only in a context that allows us to interpret what we find. To search for signs of life, we need to understand how the observed atmosphere works physically and chemically. Knowledge of the temperature and planetary radius is crucial for the general understanding of the physical and chemical processes that occur on the planet. These parameters, as well as an indication of habitability, can be determined with low-resolution spectroscopy and low photon flux, as assumed for first-generation space missions. The combination of spectral information in the visible (starlight reflected off the planet) as well as in the mid-IR (planet's thermal emission) allows a confirmation of detection of atmospheric species, a more detailed characterization of individual planets, but also the ability to explore a wide domain of planetary diversity. Having the capacity to measure the outgoing shortwave and longwave radiation, and their variations along the orbit, with the intent to determine the albedo and identify greenhouse gases would allow us not only to explore the climate system at work on an observed world but also to probe planets similar to our own for habitable conditions.

The emerging field of exoplanet search has shown an extraordinary capacity to combine research in astrophysics, chemistry, biology, and geophysics into a new and exciting interdisciplinary approach to understand our place in the Universe.

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Abbreviations

HZ, habitable zone; S/N, signal-to-noise ratio; VRE, vegetation red edge.

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